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Probabilistic Design and Management of Sustainable Concrete Infrastructure Using Multi-Physics Service Life Models

Michael D. Lepech[1], Mette Geiker[2], Alexander Michel[3] and Henrik Stang[4]

Abstract

This paper looks to address the grand challenge of integrating construction materials engineering research within a multi-scale, inter-disciplinary research and management framework for sustainable concrete infrastructure. The ultimate goal is to drive sustainability-focused innovation and adoption cycles in the broader architecture, engineering, construction (AEC) industry. Specifically, a probabilistic design framework for sustainable concrete infrastructure and a multi-physics service life model for reinforced concrete are presented as important points of integration for innovation between construction materials engineers and the broader AEC industry.

First, the paper details a probabilistic framework for design of reinforced concrete infrastructure to achieve targeted improvements in sustainability indicators. The framework, compliant with the 2010 fib Model Code requirements for environmental design, consists of concrete service life models and life cycle assessment (LCA) models. Both types of models (service life and LCA) are formulated stochastically so that the service life and time(s) to repair, as well as total sustainability impact, are described by a probability distribution.

A central component of this framework is a newly developed multi-physics service life model of reinforced concrete members subjected to chloride-induced corrosion. The corrosion model is based on stringent physical laws describing thermodynamics and kinetics of electrochemical processes including various reinforcement corrosion phenomena, such as activation, resistance, and concentration polarization as well as the impact of temperature, relative humidity, and oxygen. To describe corrosion-induced damage, a thermal analogy is used to model the expansive nature of solid corrosion products. A mechanical model further accounts for the penetration of solid corrosion products into the available pore space of the surrounding cementitious materials as well as non-uniform distribution of corrosion products along the circumference of the reinforcement. A FEM based mechanical model is used to simulate corrosion-induced cracking damage.

1. Associate Professor at Stanford University, Stanford, California 94305 (email:mlepech@stanford.edu).
2. Professor at Norwegian University of Science and Technology, Trondheim, Norway (email: mette.geiker@ntnu.no).
3. Post-doctoral Research Fellow at Technical University of Denmark, Lyngby, Denmark (email: almic@byg.dtu.dk).
4. Professor at Technical University of Denmark, Lyngby, Denmark (email: hs@byg.dtu.dk)

I. INTRODUCTION

The design and construction of civil infrastructure that is environmentally, socially, and economically sustainable over its full life cycle from extraction of raw construction materials to end of life management is increasingly desirable worldwide [*e.g.* i,ii,iii]. As a critical set of systems that support our quality of life and enable global development and progress, while consuming vast amounts of material resources and energy, it is essential that civil infrastructure is designed according to broad, long term design goals for the benefit of our planet and the current and future generations of humans, animals, and plants that will call it home.

While these goals of sustainability-focused design are well intended, the design, construction, operation, and end-of-life management of civil infrastructures that are socially, environmentally, and economically sustainable is not functionally possible today. While other engineering fields have made significant advancements in designing and implementing new materials and technologies to reduce impact, civil infrastructure designers are lagging behind. Engineering and design innovations in hybrid powertrains, vehicle aerodynamics, and battery technology have reduced the emissions of personal automobiles from 313gCO_2-eq per kilometer (generic internal combustion gasoline engine vehicle) to 180gCO_2-eq per kilometer (generic battery electric vehicle charged from a coal-derived electric power source); a 42% reduction [iv]. Innovations in composite materials fabrication, computational modeling, real-time sensing, and multi-objective design and optimization (MDO) have lead the aerospace industry toward "digital twinning" of aircraft to better design, operate, and maintain new-age aircraft like the highly fuel efficient Boeing 787 "Dreamliner" [v,vi,vii].

The grand challenge posed in this paper is for construction materials engineers and researchers to become relevant in, and ultimately drive, an accelerated cycle of sustainability-focused innovation in the design, maintenance, and management of civil infrastructure. To accomplish this, materials engineers and researchers must fully integrate their work into an emerging cadre of interdisciplinary tools. This paper details two ways, through sustainability-focused probabilistic design and multi-physics modeling, to achieve this integration and serve as a foundation for future cycles of sustainability-focused innovation in civil infrastructure design, maintenance, and management.

A. Emerging Trends and Opportunities

A number of emerging trends and opportunities in the design and operation of civil infrastructure are at the center of this grand challenge. In sum, these trends are expanding the scope of infrastructure management responsibilities from industry silos to whole lifecycle responsibility. As proposed by Sundholm *et al.* [viii], these trends and opportunities include (i) the decreasing cost and increasing capability of ubiquitous monitoring and sensing [ix,x,vii], (ii) the increasing ability to collect, store, and process large amounts of data [xi,xii,xiii], (iii) a set of improved computational modeling tools that enable high fidelity, predictive modeling of built infrastructure [v,xiv], (iv) the proliferation of online educational resources [xv,xvi,xvii], (v) the use of broader measures of performance that directly relate to user value [i,xviii,xix], and (vi) a growing acceptance of new forms of financing and governance that blur the boundaries between private and public investment [xx,xxi,xxii]. As proposed by Sundholm *et al.*, these six trends are shown in [Figure 1] as interrelated and interdependent phenomena.

A number of disciplines and professions are involved in the emerging trends shown in [Figure 1]. The move toward ubiquitous sensing is being driven primarily by electrical engineers developing new sensor and microprocessing technologies. New governance models are being formed by operations researchers, social scientists, and economists interested in new organizational structures to increase the efficiency of infrastructure project management. The creation of innovative online knowledge management systems involves researchers and professionals in education, computer science, and informatics. Innovations in data storage, cloud computing, and advanced analytics emerge from the fields of computer science, mathematics, machine learning, and statistics. The adoption of broader, more comprehensive measures of infrastructure performance is being driven by governments, societies, researchers, and practitioners who recognize the need for infrastructure that is economically, socially, and environmentally sustainable. Finally, the creation of new, multi-scale models that capture infrastructure performance (including the performance of new materials) is being driven by civil engineers, materials engineers, and material scientists.

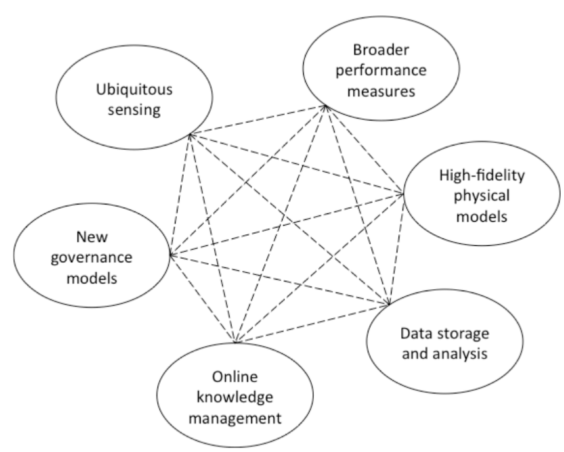

Fig. 1. Interdependent network of emerging trends and opportunities in civil infrastructure management [viii]

Building on these macro-trends, the focus of this paper is the development of two tools sets in which civil engineers and materials engineers can play a central role. The first is a probabilistic framework for sustainability-focused design of reinforced concrete infrastructure that responds to increasing demands for broader measures of infrastructure performance (*i.e.* environmental sustainability). The second is a multi-scale, multi-physics model of reinforced concrete deterioration due to depassivation and corrosion of the reinforcing steel. This model enables integration with temperature, humidity, chloride concentration, moisture, and electrical resistance sensors that are increasingly being deployed on major reinforced concrete infrastructure. Due to its complexity, the multi-physics model relies on advancements in data storage, virtual computational capacity, and advanced analytics.

II. PROBABILISTIC METHOD FOR SUSTAINABILITY-FOCUSED DESIGN AND MANAGEMENT OF REINFORCED CONCRETE INFRASTRUCTURE

As mentioned previously, the design and construction of civil infrastructure that is environmentally, socially, and economically sustainable over its full life cycle is increasingly desirable worldwide. While designing for economics has long been a focus of civil engineering, the consideration of environmental and social impacts in design is broadening the set of performance measures that are typically used. This broadening of performance measures is one of the macro trends identified by Sundholm *et al.* in [Figure 1]. While green guidelines and rating systems (*i.e.* LEED, BREEAM) have popularized green design of the built environment, these tools aren't based on probabilistic design methods that allow for rational tradeoffs between conflicting objectives, and can't account for the large uncertainties associated with environmental, social, and economic impacts that will occur decades into the future.

To enable more rational tradeoffs between economic cost, environmental protection, and social equity, and to better account for the large uncertainties associated with these impacts, Lepech *et al.* [xxiii] introduced a probabilistic framework for sustainability-focused design of reinforced concrete infrastructure. This probabilistic framework is in line with the Federation International du Beton's (*fib*) environmental design and construction requirement in the 2010 *fib* Model Code [xxiv]. Specifically, Section 3.4 of the code, "Design Principles for Sustainability", requires designers, engineers, and contractors to account for a broader set of environmental impacts, social impacts, and aesthetics through the application of life cycle concepts that begin in the design phase and continue until the final removal of the infrastructure. Environmental impacts suggested for consideration include urban air pollution, hazardous substances, global warming potential, waste material production, and resource consumption. Section 7.10 of the 2010 *fib* Model Code outlines the implementation of Section 3.4 using probabilistic methods.

The Lepech *et al.* framework consists of two types of models: (i) stochastic service life prediction models combining one or several deterioration mechanisms with a suite of limit states; and (ii) stochastic life cycle impact assessment (LCIA) models for measuring the impact of infrastructure construction, maintenance, management, and operations activities. When coupled, these two models provide a probabilistic impact envelope for the full life cycle of the infrastructure. The creation of the first model, a service life prediction model, will be discussed in Section III of this paper. The second model, which is a life cycle assessment model, and the overarching sustainability-focused design framework, are detailed in this section.

A. Sustainability-focused design framework and the definition of "sustainability"

Design for sustainability begins with measurement of the cumulative impact of a structures' initial construction, repair, and rehabilitation timeline up to the time of functional obsolescence (*i.e.* end-of-life). Cumulative impacts are expressed as midpoint environmental indicators such as global warming potential (kg CO_2-equivalents), polluted water produced (L), solid waste generated (kg), or total primary energy consumed (MJ). As seen in [Figure 2], the time at which any construction activity is performed (t_{rj}) is probabilistically characterized based on reaching a service life limit state defined by the designer or owner. The probabilistic time between repair or rehabilitation ($t_{rj+1} – t_{rj}$) is based on the chosen construction activity, the quality of the repair work, the variable nature of exposure and load conditions, the selected limit state, *etc*.

In addition to the probabilistic determination of the time of future construction activities, the cumulative impact associated with each construction activity is also probabilistically defined. This is also shown in [Figure 2]. The cumulative impact associated with a given repair, i_{rj}, can vary due to uncertainty in the construction processes actually used, uncertainty in the supply chain of construction materials and fuels, uncertainty in the effects on infrastructure users (*e.g.* how many automobiles are disrupted by a bridge construction activity), *etc*. This uncertainty is modeled stochastically, analogous to that for the life cycle timeline.

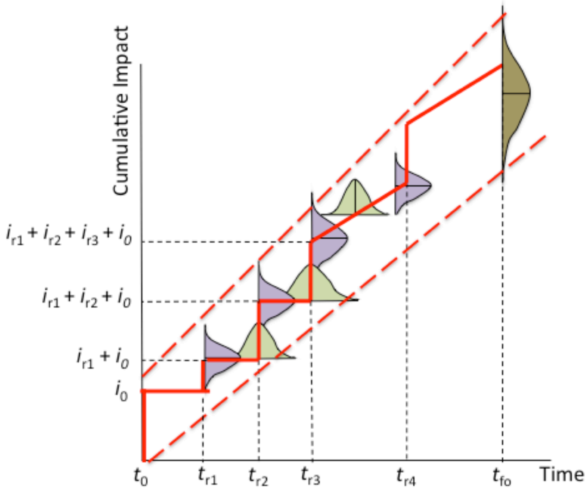

Fig. 2. Probabilistic envelope of cumulative impact for a concrete structure from time of initial construction (t_0) to functional obsolescence (t_{fo}) [xxiii]

Combining the probabilistic models for the life cycle construction activity timeline (t_{rj}) and the amount of impact (i_{rj}), a probabilistic envelope can be constructed for the entire service life from initial construction (t_0) up to the time of functional obsolescence (t_{fo}). Based on the boundaries of this envelope (dashes shown in [Figure 2]), an aggregated probabilistic characterization for cumulative impact at any time, t, for the infrastructure can be calculated.

The definition of "sustainable" can be very broad and is highly subjective. Many researchers and designers who are focused on concrete structures and concrete materials misrepresent *any* reduction of impacts associated with the structure as being "environmentally sustainable". Such concepts overlook the need to meet scientifically derived resource consumption and emission reduction targets that protect the carrying capacity of natural ecosystems in perpetuity – the basis of environmental sustainability.

A suite of environmental sustainability limit states for infrastructure design and management are emerging from the study of natural ecosystem services. Natural ecosystems provide the foundations of life on this planet. As noted by Bakshi *et al.* [xxv], natural ecosystems provide goods such as grains, biomass, water, and genetic resources. They regulate the climate, pests, floods, and air and water quality. They support photosynthesis, pollination, and biogeochemical cycles. They also have cultural, spiritual and even aesthetic value. The importance of natural ecosystems as a planetary-scale life support system (*i.e.* sustainability) is undeniable [xxvi,xxvii]. Beginning with a definition of sustainability that is built from the ongoing provision of natural ecosystem services, a suite of sustainability limit states can be defined as quantitative environmental impact reduction targets for a specific project, as described by Lepech [xxviii].

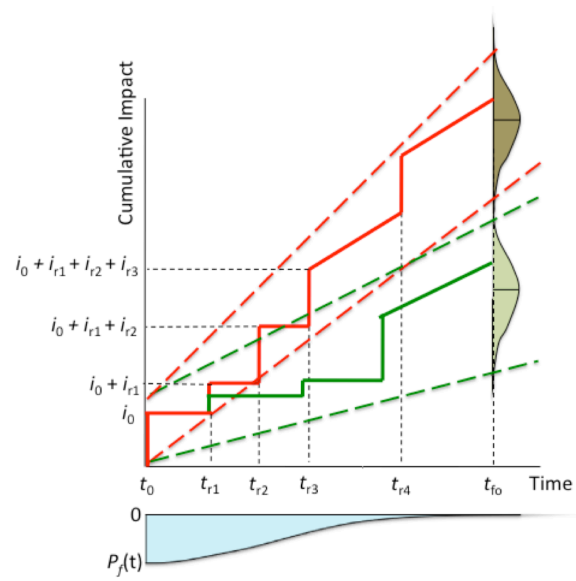

Fig. 3. Probabilistic envelopes for cumulative impact from construction to functional obsolescence for status quo (higher envelope) and alternative infrastructure designs (lower envelope). Failure probability of not meeting reduction targets (P_f) is shown as a function of time. [xxiii]

With such reductions in environmental impact reduction targets in mind, an alternative sequence of life cycle construction activities can be designed to improve upon the *status quo* infrastructure design. The comparison of the *status quo* and a more sustainable alternative is shown in [Figure 3]. Based on this, the level of impact reduction using an alternative construction activity timeline versus the *status quo* activity timeline can be estimated at any time in the future and associated with a given level of confidence for actually realizing a desired cumulative impact reduction. The probability of failing to meet a sustainability goal by implementing the new alternative design (viewed as the overlap between these two envelopes) and the failure probability, $P_f(t)$, over the life cycle are also shown in [Figure 3].

From [Figures 2 and 3], the dual nature of the framework becomes evident (service life modeling combined with life cycle modeling). Also evident is the highly connected nature of these two fields, such that the selection of any construction activity heavily influences many parts of the life cycle model. Ultimately, the use of comprehensive life cycle assessment models and predictive service life models can be used to effectively guide the design, construction, and life cycle maintenance of sustainable infrastructure through an iterative design approach.

B. Probabilistic life cycle assessment modeling

To demonstrate the construction of a probabilistic life cycle assessment (LCA) model, the repair and rehabilitation of a reinforced concrete structure, the OFU Gimsøystraumen

Bridge in Norway, is used. A summary of the OFU-Gimsøystraumen Bridge Repair Project can be found in Blankvoll [xxix]. Trial repairs were performed in 1993, 1994 and 1995 and comprised the surface repair of all concrete columns and the superstructure between piers 1 and 3 of the bridge. Further details on the LCA model construction can be found in Lepech *et al.* [xxx].

The repair activities selected to demonstrate the construction of an LCA model comparing (1) a 40mm cover replacement with water hydrodemolition, dry shotcreting, surface preparation, and surface coating and (2) an 80mm cover replacement with water hydrodemolition, dry shotcreting, surface preparation, and surface coating. An 80mm cover replacement was never considered for the actual OFU-Gimsøystraumen bridge repair, but serves only as a comparison for illustration. Detailed information on the repair materials and methods can be found in Kompen *et al.* [xxxi]. The traffic count on this bridge is approximately 3000 vehicles per day (AADT). However, no traffic was interrupted during these repairs due to their location outside of live traffic lanes. Therefore, impacts associated with construction congestion-related traffic emissions are not within the scope of the case study.

To compare the life cycle impacts of the two cover replacement activities, a life cycle inventory and impact assessment of the materials, processes, and procedures used to complete the two repairs was constructed in compliance with ISO 14040 series standards. The main sources for this data were Kompen *et al.* [xxxi], along with primary data from contractor interviews, product marketing materials for construction materials, personal safety and hygiene sheets (MSDS), and commercial life cycle inventory datasets (*i.e.* Ecoinvent, SimaPro).

For each step of the repair (hydrodemolition, shotcreting, surface preparation, surface coating), the upstream production of commercial products used, the equipment needed, the transportation associated with bringing materials to the site, and the end of life transport and landfilling of materials and construction wastes were catalogued. Uncertainty of these inputs and their impacts was also characterized. The overall environmental impact of the cover replacement activity was calculated by summing the impacts from each construction activity stage.

Monte Carlo analysis was carried out to determine the magnitude and shape of the environmental impact midpoint indicator uncertainty profiles for the two cover replacement activities. [Figure 4] shows the probability distribution for global warming potential per square meter of repair activity performed (kg CO_2-eq/m^2). Similar charts have been developed for other environmental impact midpoint indicators according to Ecoindicator 95 and ReCiPe impact assessment protocols including ozone depletion (kg CFC-11-

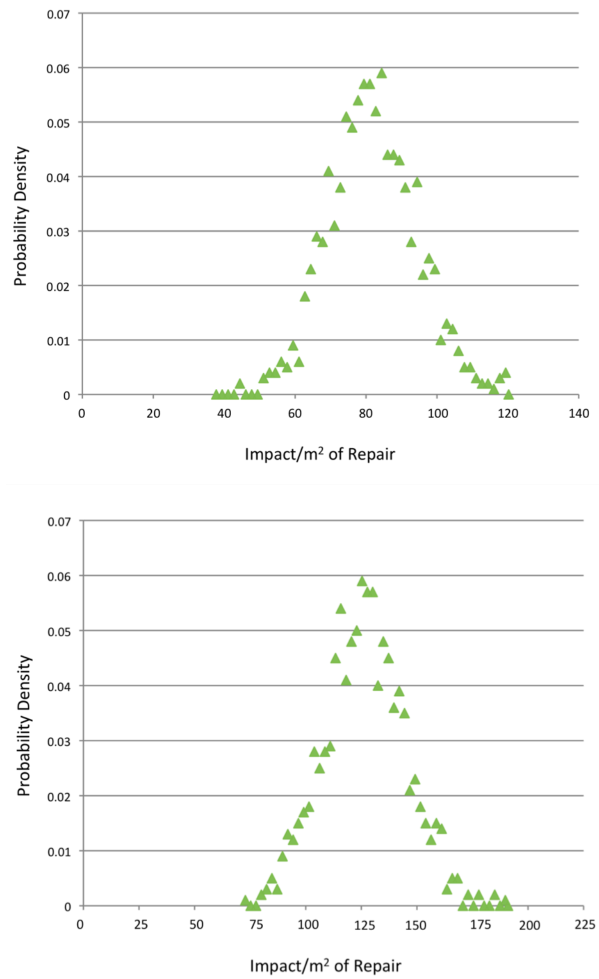

Fig. 4. Probability distribution of global warming potential impacts (kg CO_2-eq) per square meter of repair performed for (top) 40mm and (bottom) 80mm concrete cover repair activities [xxiii]

eq/m^2), acidification (kg SO_2-eq/m^2), eutrophication (kg PO_4-eq/m^2), heavy metals (kg Pb/m^2), carcinogens (kg B(a)P/m^2), summer smog (kg C_2H_4/m^2), winter smog (kg SPM/m^2), primary energy consumption (MJ LHV/m^2), solid waste generation (kg/m^2), and human health (DALYs). The full set of environmental impact midpoint indicator uncertainty profiles can be found in Lepech *et al.* [xxx].

C. Cumulative Impact Envelope Modeling

The creation of the cumulative impact envelope shown in [Figure 2] requires integration of two orthogonal probabilistic distributions. Due to the unknown parameters of the distributions that characterize the life cycle inventory and service life prediction, this integration relies on numerical methods to create a two-dimensional probability distribution field for the time-dependent cumulative impact. For simplicity, the time of future repairs can be modeled as a Markovian chain of independent, recurring, identical deterioration processes. Combining the probabilistic life cycle inventory model for one square meter of repair work with predicted service life timelines, a probabilistic envelope of cumulative impact versus time can be numerically constructed (shown conceptually in the dashed lines of [Figure 2]). An example envelope is shown in [Figure 5]. Each horizontal grouping of points in [Figure 5] represents the probabilistic time of occurrence and probabilistic impact of one repair cycle, with each point representing one repair within a bridge life cycle Monte Carlo run. Together, the horizontal groups represent the series of sequential repairs conducted over the bridge life cycle. In any future year, the cumulative impact of the repairs is a function of both the number of repairs and impact of repairs already completed. As also shown, a probabilistic distribution of the cumulative impact of repairs at any time in the future can be constructed (shown in Years 20, 60 and 100 as Gaussian for illustrative purposes) by vertically slicing through the population.

From this envelope, the likelihood of not meeting an environmental impact target in any future year can be computed. Analogous to computing a probability of failure for a structural system, the probability that the future cumulative impacts of an alternate "sustainable" concrete structural design do not meet environmental impact reduction targets, as compared to *status quo* cumulative impacts, can be envisioned as the overlap between the alternate cumulative impact envelope and a reduced *status quo* cumulative impact envelope. Likewise, the alternate cumulative impact envelope can also be compared to an absolute environmental impact target as proposed by Russell-Smith *et al.* [xxxii].

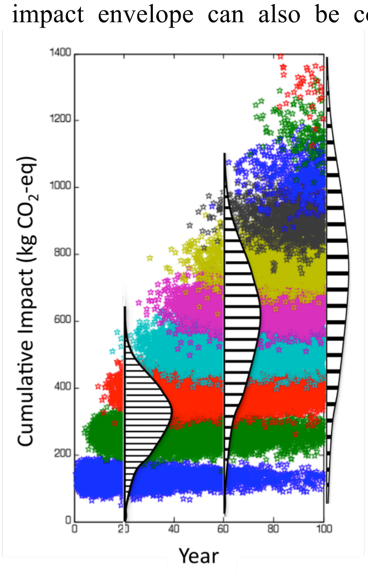

Fig.5 Example probabilistic cumulative global warming potential envelope for a structure's life cycle with characteristic probability distributions overlaid for years 20, 60, and 100 [xxx]

III. MULTI-PHYSICS MODELING OF REINFORCED CONCRETE INFRASTRUCTURE SERVICE LIFE

In addition to life cycle impact assessment, the second major component of sustainability-focused probabilistic design of reinforced concrete infrastructure is predictive service life modeling. An interdisciplinary modeling framework has been presented by Michel *et al.* and Lepech *et al.* that combines physical, chemical, electrochemical, fracture mechanical processes, and structural response models on different time and length scales in a reinforced concrete structure [xxxiii,xxxiv]. The modeling framework applies finite element method (FEM)-based models to describe (i) transport of heat and matter and chemical processes resulting in changes in phase assemblage in hydrated Portland cement, (ii) electrochemical processes at the reinforcement surface, (iii) material performance including corrosion-induced damages on the meso- and macro-scale, and (iv) structural capacity loss as a function of time.

The relationship between these multi-physics, multi-scale material and structural models is shown in [Figures 6 and 7], respectively. Fully coupled transport of heat, matter, and ions, as well as thermodynamic principles for phase changes in hydrated Portland cement, are calculated in a transport and chemical module. The deterioration module is based on stringent physical laws describing thermodynamics and kinetics of electrochemical processes including various reinforcement corrosion phenomena, such as activation, resistance, and concentration polarisation as well as the impact of temperature, relative humidity, and oxygen. Corrosion-induced damage is described in a mechanical performance module, which utilizes a thermal analogy to model the expansive nature of solid corrosion products. The mechanical performance model, furthermore, accounts for the penetration of solid corrosion products into the available pore space of the surrounding cementitious material as well as non-uniform distribution of corrosion products along the circumference of the reinforcement. The structural capacity model accounts for macro-scale effects of steel cross section reduction and material property changes, concrete cover cracking and spalling, and structural stiffness deterioration. The modeling framework is fully coupled (*i.e.* information, such as phase assemblage, moisture distribution, corrosion rate, damage state of concrete cover are constantly exchanged between the modules).

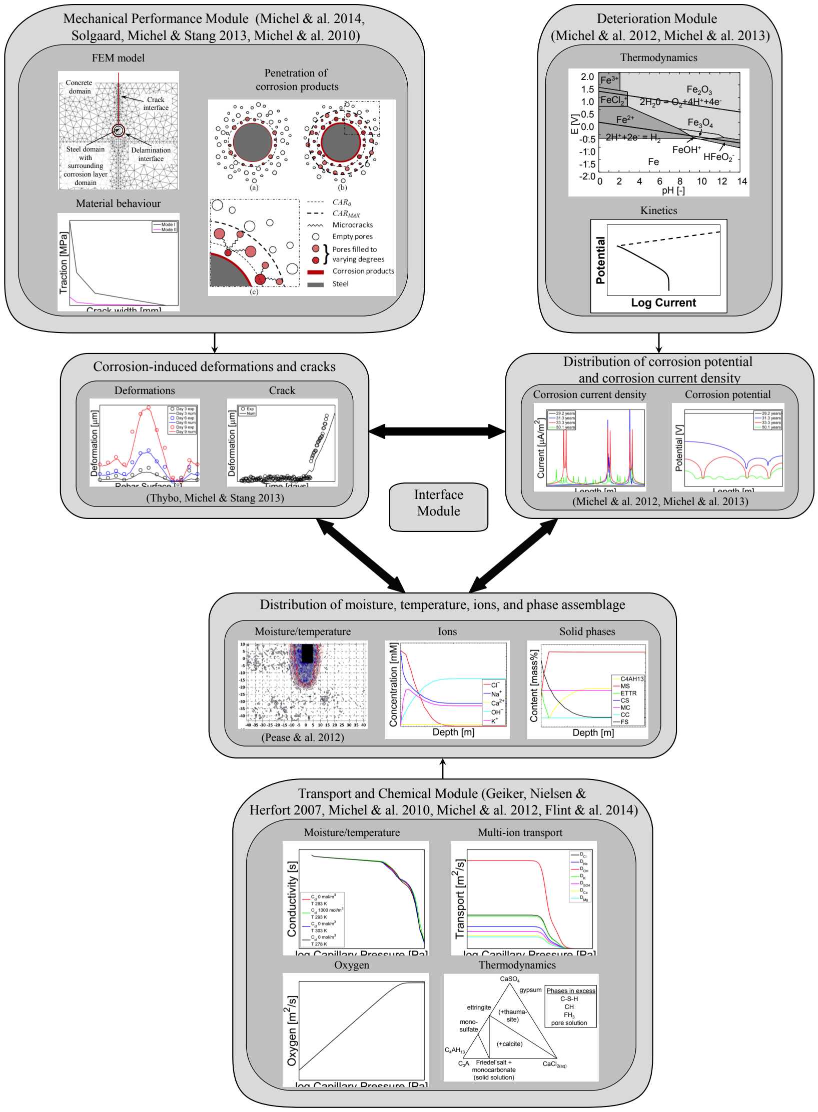

Fig. 6. Relation between mechanical performance, deterioration, and transport and chemical modules within the Material Performance Module to assess deterioration in reinforced concrete structures [xxxiii]

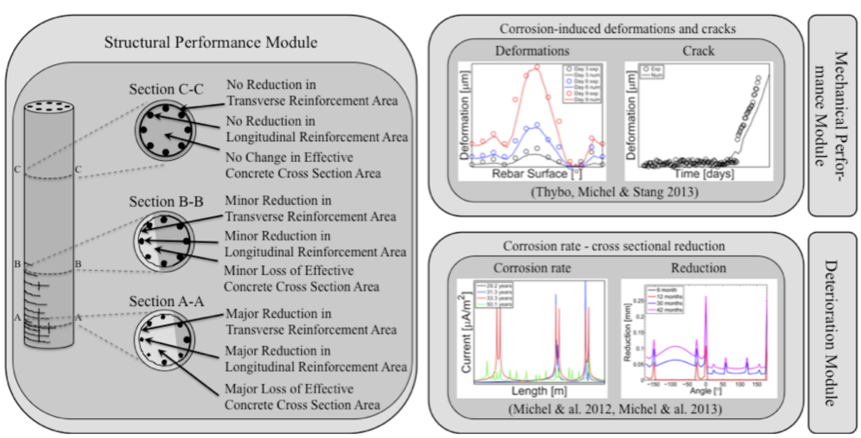

Fig. 7. Schematic representation of the computational link between the Material Performance Module (detailed in [Figure 6)] and the Structural Performance Module [xxxiv]

At the smallest scales, transport, initiation, and propagation of reinforcement corrosion in concrete is modeled using a coupled physiochemical process. Laplace's equation describes the potential distribution in concrete assuming electrical charge conservation and isotropic conductivity. Ohm's law is used to determine the corrosion current density if the potential distribution and resistivity of the electrolyte are known [xxxv]. The kinetics of the electrochemical processes are described by anodic and cathodic polarization curves. The electrochemical processes (*i.e.* the corrosion model) are coupled with transport mechanisms to account for the impact of temperature, relative humidity, and oxygen transport on corrosion. To link initiation and propagation of corrosion, when the critical chloride concentration along the reinforcement is reached, an anode forms while the rest of the reinforcement surface stays cathodic. More detailed information on the models that describe the transport of heat and matter and reinforcement corrosion, along with experimental verification of the multi-physics model, can be found in Flint *et al.* [xxxvi], Pease [xxxvii], and Michel *et al.* [xxxviii].

Corrosion-induced damage is described by a discrete cracking approach in which tension softening is modeled by multi-linear softening relationships adopted from Skocek and Stang [xxxix]. The simulated corrosion-induced damage includes cracking of the cementitious matrix (mode I fracture) and delamination at the steel-matrix interface (combined mode I and II fracture), both of which are considered along predefined crack paths.

To model the corroded reinforcement, Faraday´s law relates the rebar thickness reduction per time unit to the corrosion current density predicted by the corrosion model. The model further accounts for non-uniform formation of corrosion products along the circumference of the reinforcement as well as penetration of corrosion products into the available pore space of the surrounding cementitious matrix. Additional information on the general modeling approach can be found in Michel *et al.* [xl] and Solgaard *et al.* [xli], while more detailed information on the implementation of the fracture modeling scheme are given in Michel *et al.* [xlii,xliii] and Thybo *et al.* [xliv,xlv].

Scaling these models to the structural scale, 3D characterizations of rebar cross section reduction and concrete cracking are exported into a fiber-based finite element model that allows for dynamic structural analysis of corroded reinforced concrete members [xlvi]. This multi-scale model is used to create a physics-based timeline for future repair or replacement of reinforced concrete infrastructure. [Figure 8] shows such a probabilistic repair timeline for a reinforced concrete bridge column located in Oakland, California [xlvi]. For each year, the probability that the concrete cover will need to be patched or replaced based on a 300µm crack width limit state is shown. The sequence of distributions that describe future time-of-repair shown in [Figure 8] is analogous to those shown schematically in [Figure 2].

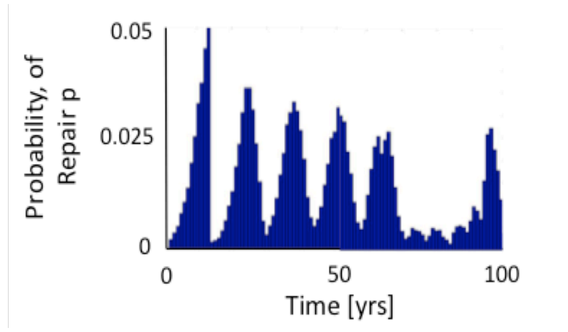

Fig.8 Probabilistic repair timeline for a reinforced concrete bridge column showing the probability of a repair activity occurring in each year [xlvi]

IV. DISCUSSION AND CONCLUSION

As mentioned previously, the grand challenge posed in this paper is for construction materials engineers and researchers to become relevant in, and ultimately drive, an accelerated cycle of sustainability-focused innovation in the design, maintenance, and management of civil infrastructure. Historically, new or improved construction materials have been created in labs and provided to the architecture, engineering, and construction (AEC) industries for adoption. Unfortunately, this has led to decades-long adoption cycles and low rates of innovation diffusion throughout this industry. For example, Ventre found that even incremental innovations in the AEC industries (*i.e.* homebuilding) could take up to 20 years to reach 70% adoption penetration, while radical innovations could take decades longer [xlvii]. A more strategic approach to drive new construction materials development and adoption is needed.

To characterize the psychology of innovation adoption, a number of classical frameworks have been proposed including those by Mansfield [xlviii], Mahajan & Peterson [xlix], and Rogers [l]. Rogers' communication-based model for innovation diffusion describes five innovation characteristics that drive diffusion; (i) relative advantage over existing practices, (ii) compatibility with existing technology and needs, (iii) complexity, (iv) trialability, and (v) observability. The six emerging trends outlined in Section IA, when fully leveraged within Rogers' diffusion framework, can help construction materials engineers push the innovation cycle – and ultimately drive sustainability-focused innovation adoption.

The six emerging trends described earlier can be mapped onto Roger' innovation diffusion characteristics. Ubiquitous sensing allows engineers and designers to better *observe* the performance of new materials in the field. The creation of improved computational tools for predictive modeling and large data processing capabilities increases the *trialability* of new materials in a reliable virtual model prior to making large, real-world investments. The proliferation of online resources to educate early adopters reduces the perceived *complexity* of new materials. New forms of private infrastructure financing and governance that require faster investor returns ensure an innovation's *compatibility with industry needs*. Finally, the use of broader performance measures allows adopters to better quantify the *relative advantages* over existing practices.

Specifically, this paper narrowly focused on two ways in which construction materials engineers can more fully integrate their work into an emerging cadre of interdisciplinary design, maintenance, and management tools. The first was through proactive development of sustainability-focused probabilistic design methods. Such methods can be used to clearly demonstrate the tradeoffs and benefits of new, more sustainable construction materials as compared to existing construction materials. The second was through creation of new multi-physics modeling tools that can make use of increasing quantities of sensed datasets and available computational power. These new models can be used to better demonstrate the long-term viability of new construction materials for which field trial results are decades away. Together these tools can begin to serve as a foundation for future cycles of sustainability-focused innovation in civil infrastructure design, maintenance, and management.

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